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This report was produced to study the use of reduced temperature, either in the form of freezing or refrigeration, as a method of mitigating the consequences of a chemical weapons transportation accident. The report studies the agents GB, VX and HD. The report discusses the use of reduced temperature to mitigate: (1) accidents resulting in a detonation or fire, (2) accidents resulting in a spill and (3) emissions from leaking munitions. It also describes concepts for reducing temperatures before a move, and maintaining reduced temperatures during a move. Cost estimates are provided for these concepts.

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TRANSPORTATION OF CHEMICAL MUNITIONS AT REDUCED TEMPERATURE

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EXECUTIVE SUMMARY

The U.S. Army's Office of the Program Manager for Chemical Munitions (OPMCM) is responsible for the disposal of the nation's stockpile of unitary chemical munitions. As a step in the implementation of this program, the Army has issued a Draft Programmatic Environmental Impact Statement which considers four alternatives: on-site disposal, disposal at a national site, disposal at two regional sites, and continued storage. Two of these alternatives involve movement of part of the stockpile to other sites where they will be destroyed. As a method of mitigating the public safety risks of such movement, OMPCM is considering the possibility of cooling the munitions to reduce the effects of accidental release of chemical agents during both on-site and off-site movement.

The report examines methods of reducing the munitions' temperature and keeping it low during transport. The effect of low temperature on hazards incurred during handling, on-site transport, and off-site transport by rail, air, or barge is also analyzed. The effect of low temperature was assessed by comparing the accidental release of agent at a reduced temperature with that at ambient temperature. In cases of atmospheric release, the comparison was performed by expressing agent release as the downwind distance to which a potentially lethal plume could be transported. The comparison was based on accident scenarios selected from a more comprehensive set of disposal program accident scenarios being analyzed (GA Technologies Inc. and H&R Associates, Inc., 1986).

The assessment shows that, for munitions containing GB or mustard, reduced temperatures may significantly reduce the consequences of accidents which result in an agent spill. The effect on VX spills is not significant due to the already very low vapor pressure of VX. It was not possible to identify net benefits for reducing the temperature for accidents involving fire or detonations. On the basis of these findings, the Army plans to consider the use of reduced temperature transportation of GB or mustard as a mitigation measure in its Mitigation Report to the Chemical Stockpile Disposal Program Enviromental Impact Statement.

If transportation at reduced temperatures is selected as a mitigation measure, munitions stored in igloos should be chilled to about 0°F by circulating chilled air through the igloo. This would require the installation of small portable refrigeration systems on a number of igloos.

Mustard bulk containers not stored in igloos at Pine Bluff, Tooele, and Umatilla could be moved to an empty igloo for chilling after the munitions stored in the igloo have been removed. At Aberdeen, an insulated, refrigerated structure could be built adjacent to the outdoor storage site and the items could be moved to the structure for chilling.

The insulated containers which will be used for transporting munitions by rail or air will maintain the reduced temperature during transit. For water transport, refrigeration is required.

The overall life cycle cost of low temperature transportation of the GB and mustard stockpile is estimated to be about $17 million over the base cost of non-refrigerated transport.

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1.0 INTRODUCTION

The United States currently maintains a stockpile of lethal chemical agents and munitions at eight locations throughout the Continental United States. Public Law 99-145 (Title 14, Part B, Section 1412) directs the Secretary of Defense to carry out the destruction of this stockpile. As required by law, an Environmental Impact Statement (EIS) must be prepared to assess the health and environmental impacts associated with the proposed disposal of the stockpile. In a Draft Programmatic EIS, issued on July 1, 1986, four alternatives are considered: on-site disposal, disposal at a national site, disposal at two regional sites, and continued storage. Two of these alternatives involve movement of part of the stockpile to either the national or regional centers for disposal.

The U.S. Army's Office of the Program Manager for Chemical Munitions (OPMCM), which is responsible for planning and implementing the disposal of the stockpile, is considering the feasibility of cooling the agents and munitions as a method of reducing the effects of accidental release of chemical agents during both on-site and off-site transportation. The MITRE Corporation has been asked to assist OPMCM in evaluating this concept by estimating the potential for hazard reduction that could result from transporting agents and munitions at reduced temperatures. MITRE was asked to consider the following off-site transportation options: rail; air; and barge (from Aberdeen Proving Ground only). The on-site transportation mode is assumed to be by truck.

1.1 Scope and Approach

The effects of reduced temperatures on the hazards resulting from accidental release of the agents GB, VX and mustard* are assessed. For the purposes of this assessment, the hazard associated with the accidental release of agent is considered to be the dispersion of agent to the environment. In cases of atmospheric release, this is expressed as the downwind distance to which a potentially lethal plume is transported.

All the major activities required of a low-temperature transportation option are considered, including:

- Chilling and refrigeration
- Handling and on-site transportation
- Off-site transportation
- Warming to ambient temperature at the disposal site

*For the purposes of this report, HD is used to represent all compounds in the mustard family (H, HT, and HD). HD has a higher freezing point than the other mustard compounds (See Table 1-1). Nevertheless, we selected HD to represent mustard because HD is present in the inventory in larger quantities than the other mustard compounds.

TABLE 1-1
FREEZING POINTS OF CHEMICAL AGENTS

AGENT	FREEZING POINT (°C)	FREEZING POINT (°F)
GB	- 56.9	-70.4
VX	- 50.0	-58
HD	14.5	58.1
H	10 to 12	50 to 53.6
HT	0 to 1.3	32 to 34.3

Source: Chemical Agent Data Sheets, 1974

The effects of reduced temperature transportation are examined for the two major classes of accidents:

- Those involving a detonation or fire
- Those involving a spill

In addition, the effect of reduced temperatures on leaking munitions is analyzed.

Methods of chilling the agent-containing items prior to shipment and maintaining them at reduced temperatures during transport are discussed in Section 2.0. Design criteria for these operations are not provided, except for features (temperature and handling) that are likely to increase hazards. A temperature at which reduced-temperature transport should be carried out is suggested. All the analysis which follows assumes that the transportation is done at the suggested temperature.

The effect of reduced-temperature movement on the agent released in the event of either detonation or fire is not dependent on the transportation mode. Thus, these accident scenarios are discussed generically in Section 3.0. Insufficient data are available on the effect of temperature on the detonation of explosives or the burning characteristics of agent to allow us to make precise judgements about accidents involving detonations or fires.

Accidental spills, with subsequent evaporation, are discussed separately in Section 4.0 for each transportation mode. The analyses of rail, air, and on-site transportation are applicable at any site. The analysis of barge transportation is limited to moving bulk containers from Aberdeen Proving Ground. Where possible, the consequences with and without reduced temperatures are compared in terms of the downwind distance to which a potentially lethal agent plume is transported.

In order to compare transportation at reduced temperatures with that at ambient conditions, it was assumed that, in either case, munitions and agent would be packed in the containers which are being designed for the protection of munitions from accidents during transport. These containers will be heavily insulated to protect against fire.

Calculations of heat transfer and evaporation were based on standard engineering practice. The assumptions used in the analysis and the available physical property data are presented in Appendix A. Sample calculations are given in Appendix B.

The general approach was to select, for detailed analysis, items from the munition inventory to represent the full range of agent quantity: bulk containers for all three agents; rockets for GB and VX; and projectiles

for HD. Accident scenarios involving these items were selected for the rail and on-site transport modes from the accident scenarios currently being analyzed by GA Technologies (Bolig, 1986[a]). An accident scenario for barge transport was also provided by GA Technologies (Bolig, 1986[b]). Since no risk analysis for air transport was available, it was assumed that an air crash on take-off or landing would rupture all munitions aboard the aircraft. Although this is a "worst-case" accident, and fewer munitions may rupture in an air crash, the relative merits of low temperature transport are not substantially affected by the quantity spilled.

The D2PC Gaussian-plume dispersion model developed by the U.S. Army (Whitacre and Myirski, 1986) was used to estimate the downwind distance potentially affected by an agent plume. The following weather conditions were assumed: an ambient temperature of 30°C (86°F), Pasquill stability E, and 1 m/sec wind velocity. These are the values used in the EIS for the "worst-case" weather conditions. All of the parameters used in the model are given in Table A-3 in the Appendix. The model gives the maximum downwind distance to a "no deaths" dosage, which is defined as the distance beyond which no fatalities are expected. Actual distances may vary substantially from those predicted by the model, but the use of model predictions is adequate for purposes of comparison.

Although the downwind distance to a "no-deaths" dosage is useful for comparison purposes, it is not directly proportional to the effect on the population. For example, a 30 percent reduction in the downwind distance will, for a uniform population density, reduce the number of potential fatalities by about 50 percent. When the distance to the "no-deaths" dosage is reduced, the distance to the "50 percent deaths" dosage is also reduced; thus, the total population potentially exposed to any given dosage level is reduced.

The approximate cost of implementing a program of refrigerated transportation was estimated. This includes the cost of chilling munitions by the most promising methods and the cost of maintaining the munitions at reduced temperature during movement. The cost estimates are not based on detailed design and thus are only accurate enough to provide the Army with sufficient information to compare refrigerated transport to other alternatives.

2.0 CONCEPTS FOR CHILLING AND MAINTAINING REDUCED TEMPERATURES

There is a wide range of temperatures to which the munitions and agent could be chilled, and a wide variety of methods could be used to achieve these temperatures. There are also many alternative methods of maintaining the temperatures during transport. The temperatures selected for the discussion in Section 2.1 below (-300°F and 0°F) (-184°C and -18°C), and the methods of achieving them cover the range of practical alternatives. Similarly, the various methods that could be used to maintain low temperatures during transport are adequately represented by the approaches discussed in Section 2.2.

2.1 Chilling Munitions and Agent Prior to Shipment

Since the greatest benefit from reduced-temperature transportation might be expected when the agent is frozen, it would appear that cooling to a temperature below the freezing point would be the method of choice. Since GB freezes at -70.4°F (-56.9°C) and VX at -58°F (-50°C), cryogenic temperatures are required. This can readily be done by immersing the munitions in liquid nitrogen until the desired temperature is reached. Using liquid nitrogen will result in the metal container being cooled to -300°F (-184°C) within a few minutes. The agent inside the container will take longer to reach its freezing point, at which time the agent in contact with the container will be at or below -300°F. Eventually, the entire munition will reach a temperature of -300°F or lower. For example a pallet of rockets could be chilled to -300°F in about three hours.

Unfortunately, for all but rockets, cryogenic chilling is not practical since the other munition types use carbon steel agent containers and carbon steel is subject to embrittlement at temperatures below about -50°F (-45°C), thus substantially increasing the likelihood of rupturing the agent container during handling and transportation.

The only munition whose metal container will not become brittle at cryogenic conditions is the M55 rocket because its metal agent containment is aluminum. Eight pallets of rockets at -300°F (-184°C) placed in an insulated container will remain frozen for about 11 days*, which would be long enough for the air transportation mode, if not for rail. While technologically achievable, a cryogenic system utilizing liquid nitrogen would require an extensive installation, similar to the front end of the Cryofracture Chemical Demilitarization Plant being considered for disassembly and destruction of munitions. The greatest drawback to using such a system for chilling rockets is that the rockets, which have a leakage history,

*Assumes sealed container with 8 inches of ordinary insulation (e.g., polyurethane foam) inside all surfaces.

might be expected to leak as a result of increased handling. Uneven rates of temperature change in different parts of the metal casing will result in differential rates of contraction which are also likely to cause leaks. Thus, the system would have to be designed to contain such leaks and to deal with contaminated nitrogen. Another disadvantage of chilling to -300°F is that handling and thawing at the disposal facility would complicate the operations there.

Compared to chilling to cryogenic temperatures, reducing the temperature to 0°F (-18°C) is a relatively simple matter. This temperature is commonly used for the transportation of many commercial goods. We have considered two methods of chilling munitions to a temperature of about 0°F:

- Chilling by immersion in a liquid coolant
- Chilling munitions in a storage magazine (igloo) or building by circulating air through a refrigeration unit

A coolant, such as a calcium chloride brine solution, ethylene glycol, or Freon may be used to chill the munitions. Since brine tends to be corrosive, ethylene glycol or Freon may be preferred. The brine, glycol, or Freon could be cooled to a temperature of -40°F by circulation through a conventional refrigeration system. Bulk containers or pallets of munitions could be immersed in the coolant until the desired temperature is reached, which would take from three to six hours, depending on the items being chilled. At the temperatures encountered in this system, no metal embrittlement would occur. The major drawback is the additional handling that would be required (as in the cryogenic system) which increases the probability of a handling accident, especially a rocket leak. Thus, agent from leakers is likely to contaminate the coolant and methods of containment and decontamination would have to be developed. This is mitigated by the fact that the Army has developed detection methods and disposal procedures for agent in ethylene glycol solutions at its Chemical Agent Munitions Disposal System (CAMDS) facility where such solutions are used as hydraulic fluids. Since the temperature differential during chilling with a coolant is substantially less than with liquid nitrogen, the probability of a leak occurring is lower, but it cannot be ruled out. Furthermore, a handling accident, such as dropping a munition, could result in agent release to the liquid coolant.

An alternative method of cooling munitions and agent to temperatures in the neighborhood of 0°F could be to circulate chilled air through the storage magazine. A system could be designed for circulating air through a refrigeration unit and cooling it to about -10°F (-23°C). This system would be similar to the systems previously used by the Army in the 1950's at Pine Bluff Arsenal to cool storage magazines of biological warfare materials to similar reduced temperatures. Munitions could be chilled

in this way by installing a small packaged refrigeration unit at each igloo or by using a smaller number of skid-mounted units which could be moved from one igloo to another. If the mobile units were used, an igloo would be cooled just before the munitions were moved. The minimum number of units required depends on the movement schedule. For example, a rail-movement schedule of 54 weeks for moving all rockets from four sites to Tooele could be met by placing 12 five-ton skid-mounted refrigeration units at each of the four sites. The design and operation of a refrigeration system for chilling munitions in an igloo is described in Appendix C. A refrigeration system using circulating air could also be used to chill munitions stored in a warehouse building if the building were properly insulated and sealed. Another possibility is to build a structure designed for use as a refrigerated building. Munitions in open storage (i.e., mustard bulk containers at three sites) could be moved to such a structure to be chilled.

A system designed to chill munitions in igloo storage has the advantage of eliminating handling prior to chilling. Those munitions not stored in igloos (mustard ton containers) would have to be moved prior to chilling. Another advantage is that the cooling rate would be slow enough to obviate leaks caused by differential cooling rates. A possible disadvantage of this system would be the increased difficulty of operating monitoring devices in the igloo at low temperatures. Serious monitoring problems are not expected because the devices are designed to operate at -10°F. There would also be the inconvenience to workers moving munitions at this temperature. Although chilling munitions in igloo storage does not increase the number of handling steps, the possibility of ice and fog formation at the entrance to the igloo could be a hazard to handling operations.

A temperature of 0°F was selected for the non-cryogenic options because much higher or lower temperatures would reduce the effectiveness of reduced-temperature movement, and because conventional refrigerated containers are designed to maintain temperatures at about 0°F. To cool the munitions much below that temperature in a reasonable time would require a coolant close to or below -50°F (-45°C), below which carbon steel is not recommended for vessel construction (Perry et al.). The temperature of 0°F has an advantage over higher temperatures because the vapor pressures of GB and VX are lower and HD takes a little longer to melt than when exposed to ambient temperatures.

The remainder of this assessment will assume that the munitions will be chilled to 0°F. At this temperature, HD is solid and, therefore, less hazardous in the event of a breached munition agent cavity. Since GB and VX are liquid at this temperature, the only advantage from chilling to 0°F derives from the lower vapor pressures of these agents. As shown in Table 2-1, there is a substantial reduction in vapor pressure when those agents

TABLE 2-1
VAPOR PRESSURE OF GB and VX AT SELECTED TEMPERATURES

Condition of Munition	Agent Temperature °F (°C)	Vapor Pressure, mm Hg GB	Vapor Pressure, mm Hg VX
Munition left in sun during hot weather	122(50)	11.3	9.8×10^{-3}
Munition at ambient conditions	86(30)	3.5	1.1×10^{-3}
Munition chilled to 0°F	0(-17.7)	0.1	1.2×10^{-6}

Source: Segers, 1986

are cooled from ambient temperature to 0°F and an even greater reduction if agent is reduced from the temperatures that might be reached if munitions are left in the sun during hot weather. The advantages and disadvantages of each of the concepts discussed above are summarized in Table 2-2.

2.2 Maintaining Reduced Temperatures During Transportation

After the munitions and agent are chilled and packed in a container for shipment, they need to be maintained at the reduced temperature (0°F) until arrival at the destination.

The simplest device for maintaining the temperature is an insulated container. The container which is being designed for use in transporting the chemical munitions is well insulated because it is designed to protect the munition from heating up during a fire. A sketch of this container is shown in Figure 2-1. Insulation is provided by 6 inches of refractory ceramic and 1/4 inch of porous honeycomb. The temperature of the agent inside the insulted container will rise less than 10°F during the rail transport time of about a week. Thus, the insulated container appears to be adequate for maintaining the reduced agent temperature during either rail or air transport.

The container could be refrigerated to maintain the reduced temperature for a longer period of time. One way to do this would be to mount a small refrigeration unit on each container. A number of units (typically, 48) may be operated on power from a central generator. Thus, a railroad train of refrigerated containers might require several generators, depending on the number of containers carried. Installation of a refrigeration unit on a container would involve penetrating the protective layers of the container. A refrigeration system adds complexity and cost to the container package.

Water transport of the Aberdeen stockpile will take several times as long as rail transport. Since the mustard is likely to melt during the transport period, full protection will require refrigeration. It is possible to install a refrigeration unit on each barge (called a "lighter"), with power supplied by a central generator located on the LASH (Lighter Aboard Ship) vessel. The lighters would have to be insulated and sealed.

The advantages and disadvantages of each of the above concepts for maintaining temperature during transportation are summarized in Table 2-3.

TABLE 2-2
ADVANTAGES AND DISADVANTAGES
OF THREE CONCEPTS FOR CHILLING MUNITIONS

CHILLING CONCEPTS	ADVANTAGES	DISADVANTAGES
A. Chilling to - 300°F with Liquid Nitrogen	• All three agents are frozen, thus substantially reducing agent release	• Additional handling required • Nitrogen likely to be contaminated with agent • For all munitions except rockets: carbon steel casings become brittle • For rockets: handling and uneven rates of metal expansion likely to cause leaks • Complicates plant operations
B. Chilling to 0°F with circulating coolant (Brine, Ethylene Glycol), or Freon)	• No metal embrittlement • Could be used for all munition types • Uses conventional refrigeration system	• VX and GB are not frozen • Additional handling required • Coolant could be contaminated with agent • For rockets: handling and uneven rates of metal contraction could cause leaks (less likely than with liquid nitrogen)
C. Chilling to 0°F with circulating Air in Storage Magazines and warehouses	• No metal embrittlement • No additional handling for munitions in igloos • Leaks during chilling unlikely	• VX and GB are not frozen • Applies only to munitions in igloos and warehouses • Agent monitoring could be more difficult • Inconvenient to workers • Chilling takes longer • Hazard due to fog and ice formation • Additional handling for munitions not in igloos (mustard ton containers)

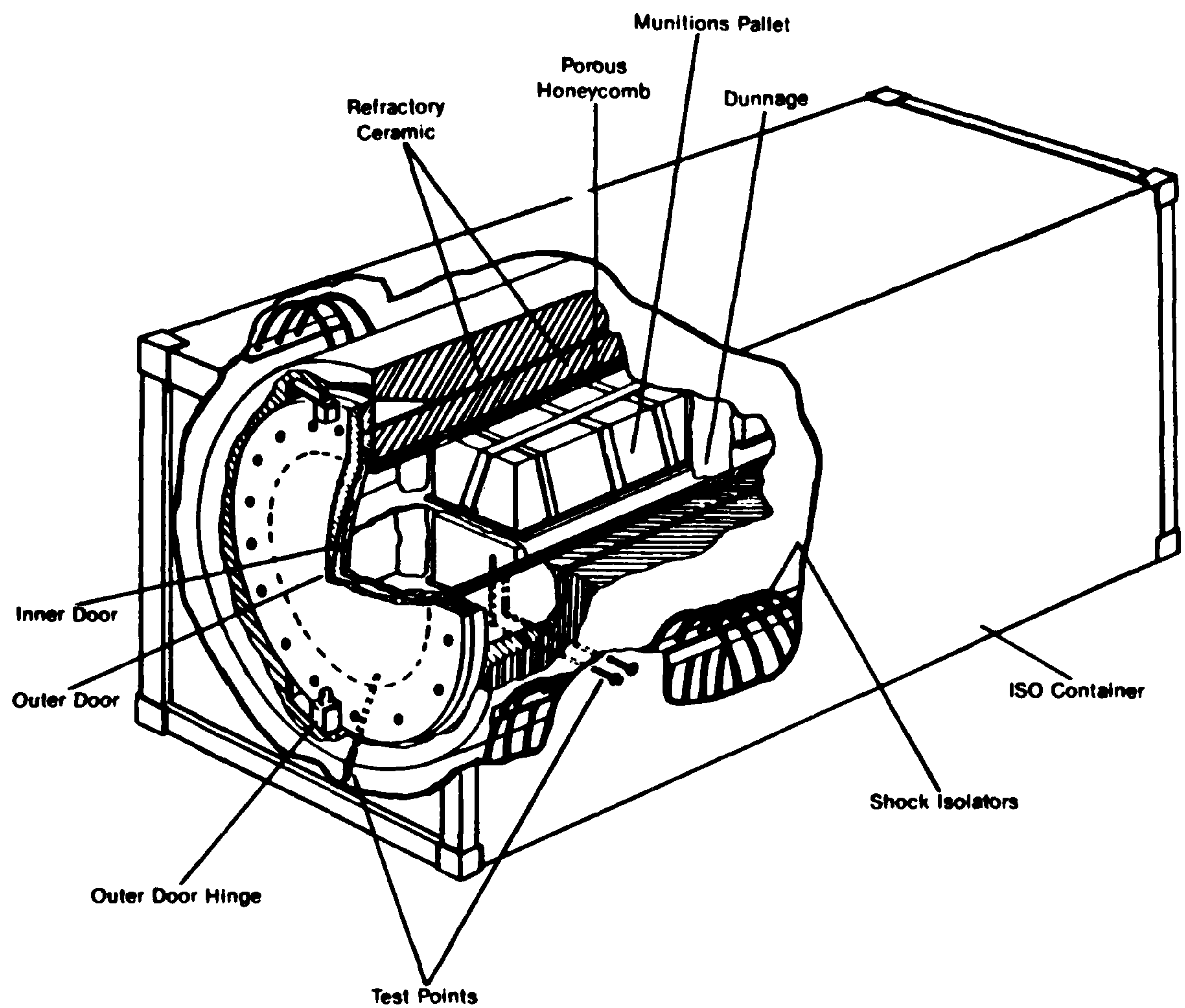

FIGURE 2-1
MUNITIONS TRANSPORT CONTAINER

TABLE 2-3
ADVANTAGES AND DISADVANTAGES OF FOUR METHODS
OF MAINTAINING REDUCED TEMPERATURES

METHODS OF MAINTAINING REDUCED TEMPERATURE	ADVANTAGES	DISADVANTAGES
A. Munition Container Transport (insulated, not refrigerated)	• Relatively easy to do • Container is being designed for transport • Munitions can be kept chilled for rail or air transport	• For trips taking several weeks, the agent vapor pressure will rise to levels which reduce the effectiveness of the original refrigeration
B. Refrigerated Munition Transport Container	• Suitable for all agents on trips of any length	• Penetration of container required • Requires power supply • Adds complexity • Additional cost
C. Refrigerated barge	• Suitable for bulk containers • Agent will remain chilled on trips exceeding 4 weeks	• Barges must be insulated and sealed • Requires power supply

3.0 THE EFFECT OF REDUCED TEMPERATURES ON ACCIDENTS RESULTING IN DETONATION OR FIRE

The effect of reduced temperatures on the agent released when a detonation or fire occurs can be treated generically because the consequences are the same for all transportation modes. The discussion of these events applies equally well to rail, air, and on-site transportation.

An investigation by GA Technologies has shown that reducing the temperature of a munition to 0°F (-18°C) does not substantially affect the probability of a detonation (GA Technologies Inc. 1986). The consequence of such an explosion, in terms of agent dispersion, might be affected if the agent is frozen. We would expect some attenuation of the downwind effect for solidified agent. In the absence of data on the particle size distribution that results from explosive dispersion of liquid and solid agents, we cannot estimate the effect of reduced temperatures on accidents involving detonations.

It is not clear whether use of solidified agent (HD) would be an advantage or a disadvantage over liquid agent in the the event of a fire. Solid agent would probably take a little longer to ignite and would burn more slowly, initially, than liquid. In some fire scenarios, where the fire is extinguished in half an hour or less, less agent might be vaporized from solid HD than from liquid. On the other hand, if the solid HD fails to ignite before it melts, or burns less efficiently than the liquid, more agent might be vaporized than if the HD were liquid because the surface temperature would be heated by the fire.

The effect of reduced temperatures of liquid agent is also uncertain. At lower temperatures, a flammable liquid is less easily ignited and may burn less efficiently (i.e., less agent may be consumed in the fire). Thus, assuming an external source of fuel, a greater amount of agent might be vaporized in a fire if agent is chilled. Chilled agent would be an advantage in the event of a fire in which the fire itself causes the munition to rupture. It would take a little longer or hotter fire to rupture the munition if the agent were chilled. In an all-engulfing fire the delay would be 10 minutes or less, depending on munition size.

While there are both potential advantages and disadvantages to solidifying or chilling agent in the event of a detonation or fire, there does not appear to be any net benefit. A full exploration of the effects of low temperature on accidents involving detonation or fire would require an extensive research and development effort. Since the expected hazard reduction is small, such an effort does not appear to be justified.

4.0 THE EFFECT OF REDUCED TEMPERATURES ON ACCIDENTS RESULTING IN A SPILL

Accidents involving agent spills have a higher probability of occurring during transportation than do accidents involving detonations or fires; but the former have lower consequences (GA Technologies Inc. and H&R Technical Associates, 1986). The effect of reduced temperatures on consequences of spill accidents is discussed in the following sections, dealing with each of the activities (i.e., on-site handling and transportation, off-site transportation, and warming at the disposal site) separately. In those cases where the effect on agent dispersion to the atmosphere depends on munition size or agent quantity, munitions of different size are selected for analysis. No site-specific analyses are provided for on-site handling and transportation, or off-site transportation by rail or air because the results are applicable to any site.

The accidents discussed in this Section are those in which the agent compartment is breached. If the agent is at an ambient temperature of 86°F (30°C), it will flow out of the container onto the ground (as all of the agents are liquid at this temperature) and will start to evaporate. The risk analysis (GA Technologies Inc. and H&R Technical Associates, 1986) assumes that up to six hours (depending on the type of accident) is required to destroy or contain the spilled agent, during which time a potentially lethal plume of evaporated agent is carried downwind. If any of these accidents occurs with agent at 0°F (-18°C), GB or VX will spill but the evaporation rate will be lower initially because the vapor pressure is lower. The agent temperature will reach within two degrees of the ambient temperature in an hour. Thus, the evaporation rate will be almost the same as for uncooled agent at the end of the first hour.

The case for HD is different because it is frozen at 0°F. As long as the HD remains frozen, little or no agent is released to the atmosphere because both the exposed surface area and the vapor pressure are low. However, soon after an accident causes the agent container to open, the HD nearest the outside of the munition will start to melt. As the melted agent flows out of the breached vessel, the next layer starts to melt. As in the case of GB and VX, the initial evaporation rate of the HD which has spilled out of the container is lower than it would be if the HD were at ambient temperatures. The melting rates, temperature increases, and evaporation rates were estimated on the basis of the assumptions given in Appendix A. Sample calculations are given in Appendix B.

4.1 On-Site Handling and Transportation of Chemical Agents and Munitions at Reduced Temperatures

In all of the programmatic disposal options, the munitions must be moved from storage and loaded on trucks (except at two sites which use forklifts for on-site movement). Trucks move the munitions, within the

site boundaries, to an on-site disposal facility or to a railhead, air-field, or barge dock, where they are loaded on the appropriate vehicles for transport to a regional or national disposal site. Finally, at the disposal site, the munitions are unloaded and transported by truck to temporary storage and the Munitions Demilitarization Building (MDB). In the following analysis it is assumed that the chilled munitions will remain in the container at about 0°F during all of the handling and on-site transportation steps from the facility in which they are chilled until they reach the MDB. Handling within the MDB is not considered.

Munitions that are moved to temporary storage could be maintained at low temperatures by keeping the munitions in the insulated or refrigerated shipping container until they are moved to the MDB. If dry ice were used to keep them chilled, the dry ice could be replenished. Continued storage in shipping containers would be extremely expensive due to the requirement for additional containers. An alternative would be to cool the storage igloo as described in Section 2.1.

4.1.1 Handling Munitions at Storage and Disposal Sites

Reducing the temperature of munitions by any method other than in a refrigerated igloo will require several additional handling steps at a storage site, as follows:

- Movement by forklift to the chilling facility
- Movement by crane into the coolant bath
- Movement by crane out of the coolant bath

These movements increase the probability that a handling accident will occur. As discussed in Section 2.0, handling prior to chilling can cause leaks which create difficulties during the chilling process. No additional handling steps are anticipated at the disposal facility. Handling refrigerated munitions may be more hazardous than handling munitions at ambient temperatures because of the possible presence of fog and ice.

The accident data base (GA Technologies Inc. and H&R Technical Associates, 1986) lists three types of handling accident scenarios resulting in agent spills from breached munitions. The munitions in these accidents are breached by being dropped, punctured by a forklift tine, or as a result of a vehicle collision. At an ambient temperature of 86°F, the agent would flow out of the container or munition onto the ground and start to evaporate. The risk analysis (GA Technologies Inc. and H&R Technical Associates, 1986) assumes that up to an hour would be required to destroy or contain the spilled agent, during which time a potentially lethal plume is carried downwind.

As noted above, evaporation rates of GB and VX are reduced by the low transport temperature for the first hour, after which the spilled agent will be destroyed or contained. For the frozen mustard, we estimate that about 11 percent (1.3 pounds) of the HD in a 155 mm projectile will have melted in one hour. Only about 2 percent (37 pounds) of the HD in a bulk container will have melted in one hour. The assumptions on which these estimates were based are given in Appendix A.

The downwind distances to which the agent plume would be transported, for accidents with and without reduced temperatures, are shown in Table 4-1. It is evident that reducing the temperature of a GB or HD bulk container substantially reduces the hazard from a spill. Since the site boundaries at all sites are at least 0.5 km from areas where handling activities are performed, reducing the temperature of HD will benefit workers on site but not effect the hazard to the public. For munitions containing VX and for projectiles containing HD, the consequences of the accidents are negligible, whether the munitions are chilled or not.

4.1.2 On-Site Transportation at Storage and Disposal Sites

On-site transportation involves moving munitions by truck from storage areas to loading terminals for rail, air, or barge. At the disposal sites it involves moving the munitions from an unloading terminal to temporary storage or the MDB and from storage to the MDB. The routes are through areas controlled by the Army.

The accident data base lists five on-site transportation accident scenario types, resulting in spills: vehicle collisions resulting in crush or puncture of munitions; earthquakes resulting in crush or puncture of munition; and an aircraft crash into a vehicle. If these accidents happen at an ambient temperature of 86°F, the agent flows out of the breached agent container onto the ground and starts to evaporate. The risk analysis assumes that it would take up to two hours to destroy or contain the agent, during which time a potentially lethal plume is carried downwind.

The reduced temperature will delay the evaporation of GB and VX. For mustard, we estimate that about 23 percent (2.7 pounds) of HD in a 155 mm projectile will melt in two hours. About 4 percent (70 pounds) of the HD in a bulk container will melt in that time. The assumptions on which the estimates were based are given in Appendix A.

The downwind distances to which the agent plume would be transported, for accidents with and without reduced temperatures, are shown in Table 4-2. The table shows that reducing the temperature of HD bulk containers virtually eliminates any serious downwind effect. Temperature reduction also yields a benefit in the case of the GB bulk container, especially in the case of an aircraft crash; but for VX bulk containers and GB rockets

TABLE 4-1
CONSEQUENCES OF HANDLING ACCIDENTS RESULTING IN SPILLS
(DOWNWIND DISTANCE TO "NO-DEATHS" BOUNDARY OF
POTENTIALLY LETHAL AGENT PLUME)
- EFFECT OF MUNITION/AGENT TEMPERATURE REDUCTION -

Accident Scenarios			Downwind Distance to "No-Deaths" Boundary (km)	
Agent Type	Munition Type	Failure Cause	No Temp. Reduction	Temp. Reduced to 0°F
GB	Bulk Con.	dropped	8.4	6.4
	Rocket	dropped	0.6	0.5
VX	Bulk Con.	dropped	0.1	0.1
	Rocket	dropped	<0.1	<0.1
HD	Bulk Con.	dropped	0.4	<0.1
	Projectile	dropped	<0.1	<0.1

Notes: The duration of the spill is assumed to be one hour because it is expected that it would take an hour to destroy or contain agent after a spill caused by a handling accident.

The following worst-case weather conditions were assumed:

Pasquill Stability E
Ambient Temperature 86°F
Wind Velocity 1 m/sec

The "no-deaths" boundary is the distance beyond which no deaths are expected from an agent plume.

TABLE 4-2
CONSEQUENCES OF ON-SITE TRANSPORTATION ACCIDENTS RESULTING IN SPILLS
(DOWNWIND DISTANCE TO "NO-DEATHS" BOUNDARY OF
POTENTIALLY LETHAL AGENT PLUME)
- EFFECT OF MUNITION/AGENT TEMPERATURE REDUCTION -

Accident Scenarios			Downwind Distance to "No-Deaths" Boundary (km)			
			No Temp. Reduction		Temp. Reduced to 0°F	
Agent Type	Munition Type	Failure Cause	Spill Duration (hr) 1	2	Spill Duration (hr) 1	2
GB	12 Bulk Con.	Aircraft crash	10.6	14.7	7.9	12.4
	1 Bulk Con.	Crush	2.9	4.0	2.2	3.4
	1 Rocket	Crush	0.2	0.3	0.1	0.2
VX	12 Bulk Con.	Aircraft crash	<0.1	0.2	<0.1	0.1
	1 Bulk Con.	Crush	<0.1	<0.1	<0.1	<0.1
	1 Rocket	Crush	<0.1	<0.1	<0.1	<0.1
HD	12 Bulk Con.	Aircraft crash	0.6	0.8	<0.1	0.1
	1 Bulk Con.	Crush	0.1	0.2	<0.1	<0.1
	1 Projectile	Crush	<0.1	<0.1	<0.1	<0.1

Notes: The maximum duration of the spill is assumed to be 2 hours because it is expected that it would take up to two hours to destroy or contain agent after a spill caused by an on-site transport accident.

The following worst-case weather conditions were assumed:

Pasquill Stability E
Ambient Temperature 86°F
Wind Velocity 1 m/sec

The "no-deaths" boundary is the distance beyond which no deaths are expected from an agent plume.

the benefit is small, as the distances are small even without refrigeration.

4.2 Off-Site Transportation of Chemical Agents and Munitions at Reduced Temperatures

The effects of reduced temperatures on consequences of spill accidents that occur during transport from storage site to regional or national disposal sites are discussed for each transportation mode separately.

4.2.1 Rail Transportation

In the accident data base (Bolig, 1986) there are two rail accident scenarios resulting in an agent spill: an accident in which the container and munition fail due to crush forces; and an accident in which the failure is due to puncture. At an ambient temperature of 86°F, liquid agent would flow out of the container or munition onto the ground and start to evaporate. The risk analysis assumes that it would take a maximum of six hours for the spill to be contained or destroyed so that evaporation ceases. During this time a potentially lethal plume of agent is carried downwind.

The evaporation rates of GB and VX are reduced only for the first hour after the spill occurs. For mustard we estimate that after six hours about 60 percent (7 pounds) of the HD in a 155 mm projectile will have melted and the temperature of the spilled agent will be about 84°F (29°C). About 12 percent (200 pounds) of the HD in a bulk container will have melted in six hours. (The assumptions on which the estimates were based are given in Appendix A and sample calculations in Appendix B.) Thus, in the case of a bulk container of HD, the benefit of reduced temperature should be substantial.

The downwind distances potentially affected by the agent plume, for accidents with and without reduced temperatures, are shown in Table 4-3. The duration of the spill is the time it would take to contain or destroy the agent. As expected, the mitigating effect of reduced temperature is substantial for HD bulk containers but negligible for smaller items containing HD. For accidents where the spill can be destroyed or contained in an hour or less, reducing the temperature lowers the distances to a "no-death" boundary by at least 24 percent for GB, although the effect is less significant for accidents that take longer to contain. It is unlikely that most accidents would take six hours for agent containment. Spill accidents involving VX appear to have negligible downwind effects in all cases.

4.2.2 Air Transportation

We have assumed that, if a plane carrying 60 rockets were to crash during take-off or landing, all of the rockets could be breached.

TABLE 4-3
CONSEQUENCES OF RAIL TRANSPORTATION ACCIDENTS RESULTING IN SPILLS
(DOWNWIND DISTANCE TO "NO-DEATHS" BOUNDARY OF
POTENTIALLY LETHAL AGENT PLUME)
- EFFECT OF MUNITION/AGENT TEMPERATURE REDUCTION -

Accident Scenarios			Downwind Distance to "No-Deaths" Boundary (km)					
			No Temp. Reduction			Temp. Reduced to 0°F		
			Spill Duration (hr)			Spill Duration (hr)		
Agent Type	Munition Type	Failure Cause	1	2	6	1	2	6
GB	1 Bulk Con.	Puncture	2.9	4.0	6.5	2.2	3.4	6.0
	1 Rocket	Puncture	0.2	0.3	0.4	0.1	0.2	0.4
VX	1 Bulk Con.	Puncture	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
	1 Rocket	Puncture	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
HD	1 Bulk Con.	Puncture	0.1	0.2	0.4	<0.1	<0.1	0.1
	7 Projectiles	Crush	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1

Notes: The maximum duration of the spill is assumed to be 6 hours because it is expected that it would take up to six hours to destroy or contain agent after a spill in a rail accident.

The following worst-case weather conditions were assumed:

Pasquill Stability E
Ambient Temperature 86°F
Wind Velocity 1 m/sec

The "no-deaths" boundary is the distance beyond which no deaths are expected from an agent plume.

Although bulk containers have a higher threshold limit for mechanical failure due to impact (GA Technologies Inc. and H&R Technical Associates, 1986) and the breaching might be limited to the two containers in the front of the plane's compartment it was assumed that all six containers on the aircraft would be breached. We have made no attempt to estimate the number of projectiles that might be breached in such an accident because projectiles have a relatively thick steel casing and may survive such an accident. If the agent containment is breached, and if there is no fire, the agent at ambient temperature will spill on the ground and start to evaporate. Since the terrain at the crash location may be similar to that in the rail transport accident scenario, we assumed that it would take a maximum of six hours for the spill to be contained or destroyed. During this time a potentially lethal plume of agent will be carried downwind.

The evaporation rates of GB and VX are reduced only for the first hour after the spill occurs. For mustard, we estimate that after six hours about 12 percent (400 pounds) of the HD in the two breached bulk containers will have melted and the temperature of the spilled agent will be about 85°F (29.4°C). The assumptions on which the estimates were based are given in Appendix A and sample calculations in Appendix B.

The downwind distances potentially affected by the agent plume, for accidents with and without reduced temperatures, are shown in Table 4-4. The duration of the spill is the time it would take to contain or destroy the agent. It is unlikely that most accidents would take six hours for agent containment. The results show that reducing the temperature of HD bulk containers greatly reduces the hazard from a spill. In cases where the duration can be limited to an hour, there is substantial benefit for reducing the temperature in the case of GB; the benefit for reduced temperature is somewhat less at longer durations. The downwind distance of the VX lethal plume is small, even when the spill duration is six hours; the effect of low temperature is negligible.

4.2.3 Barge Transportation

The barge transportation option being considered by the Army involves moving HD bulk containers from Aberdeen Proving Ground by water to Johnston Island. The bulk containers would be placed in overpacks and loaded onto barges. The barges would be loaded onto a ship which would transport all of the inventory in one trip.

The most serious spill accident scenario described in the barge risk analysis (Bolig, 1986) is a ship collision in which eight bulk containers are breached, releasing 13,600 pounds of HD into the ocean or bay. Five percent of the liquid spill remains on the surface in suspended form (perhaps as a solution in any oil that may be present as the result of

TABLE 4-4
CONSEQUENCES OF AIR TRANSPORTATION ACCIDENTS RESULTING IN SPILLS
(DOWNWIND DISTANCE TO "NO-DEATHS" BOUNDARY OF
POTENTIALLY LETHAL AGENT PLUME)
- EFFECT OF MUNITION/AGENT TEMPERATURE REDUCTION -

Accident Scenarios			Downwind Distance to "No-Deaths" Boundary (km)					
			No Temp. Reduction			Temp. Reduced to 0°F		
Agent Type	Munition Type	Failure Cause	Spill Duration (hr) 1	2	6	Spill Duration (hr) 1	2	6
GB	6 Bulk Con.	Impact	7.5	10.2	16.8	5.5	8.7	15.5
	60 Rockets	Impact	1.9	2.5	4.1	1.4	2.2	3.8
VX	6 Bulk Con.	Impact	<0.1	0.1	0.2	<0.1	0.1	0.2
	60 Rockets	Impact	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
HD	6 Bulk Con.	Impact	0.4	0.6	1.1	<0.1	0.1	0.2

Notes: The maximum duration of the spill is assumed to be 6 hours because it is expected that it would take up to six hours to destroy or contain agent after a spill caused by an air crash.

The following worst-case weather conditions were assumed:

Pasquill Stability E
Ambient Temperature 86°F
Wind Velocity 1 m/sec

The "no-deaths" boundary is the distance beyond which no deaths are expected from an agent plume.

(a) Failure caused by aircrash on take-off or landing

the accident) while the remainder sinks to the bottom. The 680 pounds of HD on the surface is expected to evaporate in 30 hours. The HD that settles to the bottom is expected to remain stable for many years (Bolig, 1986). The D2PC plume dispersion model predicts that the scenario described above will result in a potentially lethal plume with a "no-deaths" distance extending to 5.2 km.

Reducing the temperature of HD to 0°F virtually eliminates the possibility of air dispersion from such an accident. If agent containers on the ship are breached, solidified agent will not flow out. In the absence of a fire, measures to contain the agent can be taken in time to prevent agent from spilling into the water. If the accident somehow causes a bulk container to fall into the ocean it will sink before any agent has time to thaw. Thus, no agent will disperse or dissolve in oil on the surface. The hazard resulting from agent sinking to the bottom will remain.

5.0 THE EFFECT OF REDUCED TEMPERATURES ON EMISSIONS FROM LEAKING MUNITIONS

Since stored munitions have been known to start leaking, we would expect leaks to occur when the munitions are subjected to normal movement during handling and transportation. Some rocket lots have had a history of leaking when handled. While the frequency of leaking may be high relative to the accidents discussed in Sections 3.0 and 4.0, the amount of agent emitted is, in most cases, small. Many leaks have occurred which result in concentrations of approximately the permissible exposure limit (PEL)* or less (Brankowitz, 1987). It is such leaks as these that could be mitigated by chilling agent to low temperatures.

In the event that a munition started to leak during handling or transport and the cargo container also was breached or defective, agent could diffuse out of the container. The amount of agent leaving the container would depend on a number of factors, including the quantity of leaking agent, the vaporization rate inside the container, and the size of the hole in the container. Whatever the amount of agent, it would be substantially less if the agent were at reduced temperatures. If the agent were HD, it would remain solid at 0°F (-18°C) and there would, in effect, be no detectable amount of HD emitted.

In the case of GB and VX, the vaporization rate inside the container is roughly proportional to the vapor pressure. Reducing the temperature from 86°F to 0°F lowers the vapor pressure of GB from 3.5 to 0.1 mm Hg and the vapor pressure of VX from 0.0011 to 0.0000012 mm Hg. Thus, the amount of GB emitted could be reduced to 3 percent of the amount emitted if the munitions were not chilled; in the case of VX, it would be reduced to about 0.1 percent.

Thus, leaks of GB, which at ambient temperatures would result in air concentrations between 1 and 30 times the PEL, would be reduced to concentrations below the PEL if the agent were chilled to 0°F. The vapor pressure of VX is so low at ambient temperatures (0.001 mm Hg) that further reduction in vapor pressure is not likely to have a significant effect on emissions.

Mitigation of the effects of leaking munitions is particularly beneficial to air transportation because it contributes to safety by reducing the potential exposure to the crew aboard the plane. Agent from a leaking munition could diffuse into the compartment where the crew is located if the transport container were also defective. Reducing the temperature of the agent to 0°F would substantially reduce the risk of crew exposure.

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*PEL (8-hr time-weighted average) for work place:
GB = 0.0001 mg/m^3; VX = 0.00001 mg/m^3; HD = 0.003 mg/m^3 (Department of Defense, 1984, page 11-3).

6.0 WARMING TO AMBIENT TEMPERATURE AT THE DISPOSAL SITE

The viscosities of GB and VX are 4.5 cs and 140 cs, respectively, at 0°F. Since liquids flow readily at these viscosities, there will be no need to provide a facility at the disposal site to warm these agents to ambient temperatures. This has been demonstrated during disposal operations at the CAMDS facility.

The plants designed for the destruction of munitions containing HD will have a system for warming the HD. This system will be utilized whether or not reduced-temperature transportation will be implemented for these munitions. This is because it is necessary to thaw mustard munitions stored at locations, such as Tooele Army Depot, which routinely experience very cold winter temperatures. The system should be designed to warm the munitions and agent slowly enough to prevent leaks caused by differential rates of metal expansion. Rapid heating can cause vessels containing solids to rupture.

Since handling related to warming mustard munitions will exist whether or not the Army uses the low-temperature option, there does not appear to be any additional hazard at the disposal site attributable to low-temperature transportation.

7.0 COST ESTIMATES

In the absence of precise design parameters, accurate cost estimates cannot be made. It must be emphasized that the costs contained in this report are based on concept designs and not a detailed design. The estimated costs provided herein may differ substantially from detailed estimates which will be prepared prior to implementation of any of the concepts outlined in this report. Since these costs are preliminary in nature, they should be used only for purposes of comparing alternatives. The cost estimates are generic, not site-specific.

Installed (capital) cost includes equipment, installation, and labor; operating cost includes labor, maintenance and utilities for three years. The term life cycle cost includes both installed cost and operating cost.

The cost estimates given below are for the most promising alternatives. Costs are provided for chilling munitions by two methods: (1) chilling the existing igloos, and (2) chilling in a structure built or modified for the purpose. Costs are also given for maintaining low temperature during transport.

7.1 Cost of Chilling Munitions

The life cycle cost of a single igloo refrigeration unit is approximately $230,600. As indicated in Appendix C, it appears that 12 such units mounted on skids should be adequate at all sites storing rockets (Anniston, Lexington-Blue Grass, Umatilla, Pine Bluff, and Tooele) and 8 units should be adequate at Pueblo, where no rockets are stored. Thus, the total cost of installing and operating igloo refrigeration systems is about $15 million. If no refrigeration is carried out at Tooele, except for GB bulk containers, the savings are estimated to be $2.4 million. If no refrigeration is carried out at Anniston (for the Regional Alternative) the savings are estimated to be $2.4 million.

The life cycle cost for a refrigerated structure designed to chill bulk containers is approximately $2 million. Such a structure is necessary at Aberdeen Proving Ground. At Pine Bluff and Tooele Army Depot, the cost of moving the mustard containers to igloos for refrigeration is about $1 million, versus the option of building new structures for this purpose which would cost $9 million. At Umatilla, installing and operating a refrigeration system in the existing warehouse would cost $600,000 versus moving the mustard into igloos for refrigeration which would cost $300,000.

7.2 Cost of Maintaining Reduced Temperatures During Transportation

Since the insulated containers which will be used for rail or air transportation will maintain the chilled munitions at reduced temperatures during rail or air movement, no refrigeration is needed during movement. Therefore, there is no additional cost for maintaining reduced temperatures during rail or air movement. Adding refrigeration units to the container would cost about $8,400 per container.

Since transportation by water is longer than by rail or air, refrigeration will be needed if the mustard is to be maintained at a reduced temperature until it reaches Johnston Island. The total life cycle cost of the barge refrigeration system is $2 million, on a LASH vessel for the transportation of the bulk containers of mustard at Aberdeen Proving Ground.

7.3 Total Cost

The total life cycle cost of low-temperature transportation of the GB and mustard stockpile by rail or air is about $17 million above the cost of non-refrigerated transportation.

The total cost is lower if no chilling is done at the receiving sites. This could be considered if a better way of mitigating spills during on-site movement is found which would eliminate the need for refrigeration during on-site moves to the disposal plant. Because of the distance from the installation at Tooele to the site boundary, agent spills (except those involving GB bulk containers) are not a hazard to the general public beyond the site boundary. If no munitions are chilled at Anniston (a receiving site for the Regional Alternative) the savings are $2.4 million. If no munitions, except GB bulk containers, are chilled at Tooele, the savings are also $2.4 million. Thus the total cost for the Regional Alternative could be reduced to about $13 million and, for the National Alternative, reduced to $15 million.

If water transportation is used for the Aberdeen stockpile, the additional cost is about $2 million.

8.0 SUMMARY AND CONCLUSIONS

There are both advantages and disadvantages to transportation at reduced temperatures, depending on the agent, the type of munition, and the transportation mode. The discussion below summarizes the results of the analysis separately for each agent. The discussion does not address accidents involving detonations or fire because we were unable to identify net benefits for reducing the temperature in such accidents (see Section 3.0). The conclusions are also summarized in Table 8-1.

8.1 Munitions Containing GB

All of the methods of chilling munitions described in Section 2.1 have some disadvantages. Chilling inside the storage magazine is the simplest method and appears to present the fewest serious problems, especially for rockets. This is a feasible option for GB-containing munitions because these are all stored in igloos. Chilling by immersion in ethylene glycol is more complex, requires additional handling, and could require the disposal of contaminated ethylene glycol. Although the Army has developed a method of monitoring and destroying contaminated ethylene glycol, the occurrence of contamination would disrupt the refrigeration process and substantially delay the transportation schedule. Thus, igloo refrigeration is the preferred method of chilling GB munitions.

Reduced temperature provides significant reduction in the consequences of handling and on-site transportation accidents involving bulk containers, although the benefit for rockets is smaller. These benefits from reducing temperature apply to both the storage sites and the disposal sites. At Tooele Army Depot, however, the site boundary lies beyond the "no-deaths" distance for all spill accidents except those involving GB bulk containers. Thus, there is no impact to the public from spill accidents involving the smaller munitions, even without the mitigating effect of low temperature. It should be emphasized that for on-site transportation, other methods of mitigation may exist which are more cost effective than refrigeration. This should particularly be considered where the MDB is located very close to the storage site. In such cases, refrigeration could be used, but better ways to mitigate a spill may exist.

There is substantial mitigation of the effects of off-site accidents involving GB, especially for those accidents in which the agent can be contained or destroyed in an hour. The effects of leakers are mitigated — a benefit which could be important for the rail transportation option, and even more important for air transportation.

The preferred method of maintaining a low temperature during rail or air transit is the use of the insulated container being designed for use in transporting chemical munitions. This will allow munitions to be

TABLE 8-1
BENEFITS OF TRANSPORTATION AT REDUCED TEMPERATURE

	Effect of Reduced Temperature on Consequences of:		
Agent	Fire or Detonation	Leaking Munition	Spill
GB	No perceived benefit	Substantial benefit	Substantial benefit
VX	No perceived benefit	Insignificant benefit	Insignificant benefit
HD	No perceived benefit	Substantial benefit	Substantial benefit for bulk containers

transported at low temperature without adding special refrigeration equipment to the container. Refrigeration of the container has the advantage of keeping the munitions cold longer, but has the disadvantages of costing more (about $8,400 per container), being mechanically more complex and adding penetrations to the container. Adding refrigeration to the containers does not appear to be necessary because the rail and air transport times are short.

In summary, for GB munitions, the Army is considering the use of refrigeration as a mitigation measure in its Mitigation Report to the Chemical Stockpile Disposal Program Environmental Impact Statement.

8.2 Munitions Containing VX

The vapor pressure of VX is so low that most spill accidents have no significant effects at ambient temperatures. The downwind distance of lethal plumes in most cases is under 0.1 km. The only accident in which reduced temperature provides some mitigation is the crash of a plane carrying VX bulk containers. It should be noted that there are no VX bulk containers to be transported at Lexington-Blue Grass Army Depot or Aberdeen Proving Ground, the sites from which the Army is considering air transportation.

As a result of the analyses presented in this study, the refrigeration of VX will not be pursued further by the Army in the Mitigation Report to the Chemical Stockpile Disposal Program Environmental Impact Statement.

8.3 Munitions Containing HD

Since HD can readily be solidified, there are several benefits which reduced temperature transportation can readily provide, such as reducing the immediate hazard zone during a spill and preventing leakage. Some disadvantages for refrigerating mustard munitions are presented by the logistics of accomplishing the refrigeration operation and maintaining low temperatures during transit.

As with GB, all of the methods of chilling munitions described in Section 2.1 have some disadvantages. Chilling inside the storage magazine appears to present the fewest problems. This presents an added logistical problem, as bulk one-ton containers stored at Aberdeen Proving Ground, Pine Bluff Arsenal and Tooele Army Depot are stored outside.

For the bulk one-ton containers stored outside, several possible solutions exist. The one-ton containers could be moved to refrigerated buildings designed and built nearby for this purpose. The items could then be chilled in these new buildings prior to shipment. A second alternative is that at Pine Bluff and Tooele these containers could be chilled

by moving them into nearby igloos equipped with skid-mounted refrigeration units after the GB or VX munitions in these igloos had been removed. A third alternative is dipping the one-ton containers in ethylene glycol.

Chilling inside existing igloos seems to be the preferable solution from both a cost and handling perspective. It is certainly more economical than building a special refrigeration building. It is also preferable to the glycol dip because the immersion process is more complex, requires more handling, and could generate contaminated coolant for disposal in the event a container leaked during processing. Although replacement of defective or brass plugs and valves would greatly reduce the chance of a leaking bulk container, the increased possibility of a handling accident or coolant contamination are still disadvantages.

Another factor in whether to consider the refrigeration of mustard is what effect refrigeration has on the hazard zones from potential spills. The effect of reduced temperature on the consequences of handling accidents is minimal because the site boundaries at all sites are at least 0.5 km from areas where handling is done. The maximum downwind distance to a "no-deaths" dosage is less than 0.5 km for an accident involving an HD spill, even without reducing the temperatures.

The downwind distance to a "no-deaths" dosage for an on-site transportation accident involving an HD bulk container spill is reduced from 0.8 km to 0.1 km by chilling the HD. Thus, reduced temperatures greatly reduce the hazards from such accidents at those sites (e.g., Aberdeen Proving Ground) where on-site transportation activities may be carried out at distances less than 0.8 km from the area site boundaries. At those sites where the site boundaries are more than 0.8 km from the area where such an accident can occur, chilling the HD yields no benefit to the public.

There is a significant reduction in the effects of off-site transportation accidents involving bulk containers. The effects of spills resulting from rail and air accidents are greatly reduced. In the barge accident the evaporation of agent to the air from mustard floating on the water's surface is eliminated, but any hazard caused by agent that sinks to the bottom of the bay or ocean will remain.

The preferred method of maintaining a low temperature during rail or air transit is the use of the insulated container which is being designed for use in transporting chemical munitions. For movement by water from Aberdeen, refrigerated LASH lighters could be used.

In summary, for HD munitions, the Army is considering the use of refrigeration as a mitigation measure in its Mitigation Report to the Chemical Stockpile Disposal Program Environmental Impact Statement.

8.4 Cost

The cost of low-temperature transportation of the GB and mustard stockpile is estimated to be about $17 million above the cost of non-refrigerated transportation. This is based on the following assumptions:

- All of the GB and mustard stockpile will be refrigerated, including that subjected only to on-site movement.
- All items stored in igloos will be chilled to 0°F in storage. Twelve movable refrigeration units will be installed at each of five sites and eight units at one site.
- Items not stored in igloos will be chilled by moving them to refrigerated igloos or structures built for that purpose.
- All items will be transported by rail and air in the insulated containers now being designed for chemical munition transport.

If Aberdeen stocks are moved by water, the additional cost of refrigerated barge transport is $2 million.

If no refrigeration is carried out at Anniston, the total cost is reduced by $2.4 million. If only GB bulk containers are refrigerated at Tooele, the total cost is also reduced by $2.4 million.

APPENDIX A

INFORMATION AND ASSUMPTIONS USED IN THE ANALYSIS

TABLE A-1
AGENT PHYSICAL PROPERTIES

	GB	VX	HD
Heat of fusion, Btu/lb	37.6	21.2	43.9
Heat of evaporation, Btu/lb	141	--	--
Density, g/cm^3			
@25°C	--	1.0083	1.2685
20°C	1.0946	--	--
0°C	1.1163	1.0269	1.2921
-20°C	1.1372	1.0413	1.3104
-40°C	1.1573	1.0553	1.3282
Viscosity, cs			
@25°C	1.283	9.958	--
0°C	2.310	35.4	--
-20°C	5.259	182.4	--
Heat Capacity (solid), Btu/(lb)(°F)	0.319	0.392	0.273
Heat Capacity (liquid), Btu/(lb)(°F)			
@25°C	0.377	0.415	0.319
0°C	0.365	0.399	--
-20°C	0.356	0.387	--
-20°C	0.348	0.376	--
Thermal conductivity (liquid), Btu/(hr)(ft)(°F)			
@25°C	0.0759	0.0748	0.0804
-20°C	0.0814	0.0789	--
Freezing point, °F	-70.4	-58	58.1

Equations for calculation of vapor pressure (P, mm Hg) as a function of T, °K

$$\log_{10} P = -\frac{A}{T} + B$$

Where A and B have the following values:

	A	B
GB	2478	8.725
VX	4747	12.69
HD	3151	9.599

TABLE A-1 (Concluded)
AGENT PHYSICAL PROPERTIES

Sources

a. All data except freezing points and vapor pressures from Fournier, 1983
b. Freezing points and vapor pressures from Chemical Agent Data Sheets, 1974.
c. Vapor pressure equations from Segers, 1986.

TABLE A-2
ASSUMPTIONS USED IN HEAT TRANSFER COMPUTATIONS

Heat Capacity, Btu/(lb)(°F)	
Metal components of munitions	0.19
Non-metal components of munitions	0.3
Dunnage	0.57
Concrete	0.156
Air	0.238
Earth	0.26
Heat transfer coefficients, Btu/(hr)(ft^2)(°F)	
Air to surface, forced connection	4
Air to surface, 1 m/sec wind velocity	2
Air to surface, enclosed area with natural convection	1
Air to surface, enclosed area without natural convection	0.4
Temperatures, °F	
Ambient	86
Flame during fire accident	1850
Surface area of agent contained in munition, ft^2	
Bulk container	48.2
Rocket	2.8
Projectile	1.9
Surface area of metal casing around agent, ft^2	
Bulk container	62
Rocket	2.9
Projectile	2.4
Conductivity, Btu/(hr)(ft)(°F)	
Foam insulation	0.015
Metal (steel)	26
Non-metal components of munitions	0.8
Dunnage	0.12
Concrete	0.54
Earth	0.13

TABLE A-3
ASSUMPTIONS USED IN CALCULATION OF AGENT PLUME DISTANCES (D2PC DISPERSION MODEL)

Meteorological Condition	"Worst Case"
Atmospheric Stability Class	E
Wind Speed (Meters/Sec)	1
Ground Temperature (°C)	30
Mixing Layer Height (Meters)	750
Vapor Depletion Code	1
Frost Constant	0.25
Surface Roughness Parameter (Cm)	1
Surface on which spill occurs	
Handling Accidents	Non-porous
All other accidents	Gravel

TABLE A-4
COMPONENTS OF MUNITIONS USED IN ANALYSIS

	Weight of Component (lbs)		
	Metal	Agent	Other
Bulk container (GB)	1600	1500	-
Bulk container (VX)	1600	1600	-
Bulk container (HD)	1600	1700	-
Rocket (GB)	23.8	10.7	22.5
Rocket (VX)	23.8	10.0	22.5
155 mm Projectile (HD)	82.5	11.7	0.8

APPENDIX B

SAMPLE CALCULATIONS

B.1 ESTIMATE TIME REQUIRED TO CHILL MUNITIONS

Scenario: Munitions packed in pallets are placed in an igloo. Air is circulated from the igloo through a 5-ton refrigeration system outside the igloo. (See Appendix C).

Sample calculation: time required to cool GB to 0°F in an 80-ft, 26.5-ft diameter igloo containing 175 rocket pallets.

Assumptions:

- Initial temperature: 60°F inside igloo
- Concrete inner wall and floor (average thickness = about 8") and earth cover (average thickness = 3.2 feet) are chilled
- Power requirement for blower = 2 HP
- Heat transfer coefficients and conductivity from Table A-2, except as follows:
  - The surface film coefficient inside the igloo (i.e., igloo or munition surface) is assumed to be 1 Btu/(hr)(°F)(ft^2) (most air movement caused by natural convection).
  - Heat transfer by convection in liquid agent is assumed to be 20 Btu/(hr)(°F)(ft^2) (based on Perry, Chilton and Kirkpatrick, page 10-30)
  - Heat Conductivity of fiberglass plastic firing tube around rocket [0.12 Btu/(hr)(°F)(ft^2)] is based on assumption that rocket fits tightly inside tube.

Other Parameters used in calculations:

Volume of igloo = 22,000 ft^3
Inside area of igloo = 6000 ft^2
Weight of concrete = 600,000 lbs
Weight of earth = 1.73×10^6 lbs

	Heat Transfer Distance, ft
Firing tube	0.015
Metal	0.02
Concrete	0.667
Earth	3.2

Step 1: <u>Estimate the amount of heat removed by the refrigeration system</u>

a. Assuming 40 days cooling time, estimate temperature of igloo. To calculate maximum amount of heat removed from the igloo walls, floor and surrounding earth, assume that the inside surface of the igloo is at 0°F for 40 days (since the temperature gradually cools to that temperature, the actual average temperature is higher than 0°F).

For a solid of infinite thickness, initially at 60°F, whose surface is cooled to 0°F at time t = 0, the temperature (T) at a distance (y) from the surface is given by the following expression (Bird et al. 1960, pp 352-354):

$$\frac{T}{60} = 1 - \text{erf} \frac{y}{\sqrt{4 \alpha t}} \qquad \text{(Eq. 1)}$$

where is the thermal diffusivity,

$$= \frac{\text{conductivity}}{\text{Density * Specific Heat}}$$

	Values of α, ft^2/hr
Concrete	0.024
Earth	0.00625

Solving for T at t = 40 * 24 hrs we obtain the following temperature profile:

Depth, ft		Temperature, °F
Concrete	Earth	
0	-	0
0.667	0	5
-	1	17
-	2	29
-	3	39
-	3.2	41

	Temperatures after 40 days	
	Average, °F	Decrease, °F
Concrete	2.3	57.7
Earth	23.6	36.4

b. Heat transfer through the igloo roof.

The igloo arch is divided into 3 sections according to the depth of earth. The surfaces for heat transfer are:

Surface	Average Depth, ft		Area, ft^2		
	Earth	Concrete	Outside Earth	Outside Concrete	Inside
A Section	2	0.5	1320	1150	1110
B Section	4	0.667	1500	1165	1110
C Section	6	1.167	1710	1210	1110
Front*	0	0.667		275	275
Rear	6	1.0	420	275	275

*Assume front and door are insulated with 2" of insulation with conductivity of 0.02 Btu/(hr)(°F)(ft).

$$U_A = \left(\frac{0.5\ ft * 1110ft^2/1130f^2}{0.54Btu/(hr)(°F)(ft)} + \frac{2ft\ *1110ft^2/1235ft^2}{0.13Btu/(hr)(°F)(ft)} + \frac{1}{1Btu(hr)(°F)(ft^2)} + \frac{1110ft^2/1320ft^2}{4Btu/(hr)(°F)ft^2} \right)^{-1}$$

$$= 0.063\ Btu/(hr)(°F)(ft^2)$$

$$U_B = \left(\frac{0.667 * 1110/1138}{0.54} + \frac{4*1110/1333}{0.13} + 1 + \frac{1110/1500}{4} \right)^{-1}$$

$$= 0.036\ Btu/(hr)(°F)(ft^2)$$

$$U_C = \left(\frac{1.167*1110/1160}{0.54} + \frac{6*1110/1460}{0.13} + 1 + \frac{1110/1750}{4} \right)^{-1}$$

$$= 0.026\ Btu/(hr)(°F)(ft^2)$$

$$U_{Front} = \left(\frac{0.066}{0.54} + \frac{1}{4} + \frac{0.167}{0.02} \right)^{-1} = 0.092\ Btu/(hr)(°F)(ft^2)$$

$$U_{Rear} = \left(\frac{1}{0.54} + \frac{6\ 275/348}{0.13} + 1 + \frac{275/420}{4} \right)^{-1} = 0.025\ Btu/(hr)(°F)(ft^2)$$

Assume an average temperature differential (Δt_m) of 62°F. Heat transfer (Q) through igloo roof during 40 x 24 hours:

$$Q = [(0.063 + 0.036 + 0.026)\ Btu/(hr)(°F)(ft^2) * 1110ft^2$$
$$+ (0.092 + 0.025)\ Btu/(hr)(°F)(ft^2) * 275ft^2] * 62°F$$
$$* 40 * 24\ hr \qquad = 10.18 \times 10^6\ Btu$$

c. Compute total heat removed by refrigeration unit.

	Amount (lbs)	Specific Heat Btu/(lb)(°F)	Temp. Change (°F)	Heat Removed (10^6 Btu)
Agent	28,088	0.37	60	0.62
Metal	62,475	0.19	60	0.71
Propellant	59,002	0.3	60	1.06
Dunnage	88,625	0.57	60	3.03
Concrete	6×10^5	0.156	57.7	5.40
Earth	1.73×10^6	0.26	36.4	16.37
Air	1,700	0.24	60	0.03
Heat through igloo roof				10.18
Heat from 5HP air blower 12,800 Btu/hr * 40 * 24 hr				12.28
				49.68

Step 2: Estimate Required Refrigeration Load

$$\text{Refrigeration requirement} = \frac{49.68 \times 10^6\ Btu}{12{,}000\ Btu/(hr)(ton) * 40\ days * 24\ hr/day} =$$

4.3 tons of refrigeration. Therefore, 5-Ton refrigeration unit is adequate to cool igloo and contents in about 40 days.

Step 3: Compute the Temperature Differential Required to Cool Agent to 0°F

The overall heat transfer coefficient (U_{AGT}) for the agent in the agent compartment, with the rocket inside its firing tube, is computed as follows:

$$U_{AGT} = \left(\frac{1}{1\ Btu/(hr)(°F)(ft^2)} + \frac{0.02\ ft}{26\ Btu/(hr)(°F)(ft)} + \frac{0.015\ ft}{0.12\ Btu/(hr)(°F)(ft)} + \frac{1}{20\ Btu/(hr)(°F)(ft^2)} \right)^{-1} = 0.85\ Btu/lb(°F)(ft^2)$$

Heat removed (Q_A) from agent in 175 pallets of rockets:

$$Q_A = 28{,}088 \text{ lb} * 0.37 \text{ Btu/(lb)(°F)} * (60 - 0)\text{°F} = 0.62 \times 10^6 \text{ Btu}$$

Heat transfer area = 2.9 ft^2/rocket x 175 pallets x 15 rockets/pallet
= 7,613 ft^2

Average temperature differential (Δt_m) between the air and the agent:

$$\Delta t_m = \frac{0.62 \times 10^6 \text{ Btu}}{0.85 \text{ Btu/(hr)(°F)(ft}^2\text{)} * 7613 \text{ ft}^2 * 40 \text{ days} * 24 \text{ hr/day}} = 0.1\text{°F}$$

The agent temperature remains within about 0.1°F of the chilled air temperature during the cool-down period.

B.2 ESTIMATE DELAY IN MUNITION RUPTURE DURING FIRE

Sample calculation for GB bulk container.

It has been estimated that a bulk container will fail in 36 minutes if subjected to direct exposure in an all-engulfing fire at 1850°F (Bolig, 1986[a]).

Assuming that this is the time required to heat the container from the ambient temperature to 400°F, the time required to heat from 0°F to 86°F should represent the delay which would result if it were chilled to 0°F.

Since the radiant heat transfer to the outer shell is approximately the same whether or not the munition is chilled, the amount of heat transferred to the munition is a function of the heat capacity, the heat transfer coefficient, and the temperature differential between the other shell and the agent within.

From Table A-1, the estimated heat capacity of GB between 0°F and 86°F is about 0.37 Btu/(lb)(°F); and between 86°F and 400°F is about 0.43.

Assume mean temperature of outside metal surface is about 1000°F.

T = time required to heat from 0°F to 86°F

$$T = 36 \text{ minutes} * \frac{\left(1000 - \left(\frac{400 + 86}{2}\right)\right)^{\circ}F * (86-0)^{\circ}F * 0.37 \text{ Btu/(lb)(}^{\circ}F)}{(400-86)^{\circ}F * 0.43 \text{ Btu/(lb)(}^{\circ}F) * \left(1000 - \frac{(86-0)}{2}\right)^{\circ}F}$$

$= 6.7$ minutes

Note: This calculation is not highly dependent on the outside surface temperature of the munition. For example, if outside surface temperature is 1200°F, T = 7.0 minutes

B.3 ESTIMATE RATE OF SOLID AGENT TEMPERATURE RISE AND THAWING AFTER ACCIDENT

Scenario: An accident occurs in which the agent containment fails. Agent flows out of break in casing as it thaws.

Sample calculation for HD bulk container.

Basis:

- Ambient temperature = 86°F
- Initial agent temperature = 0°F
- Heat transfer coefficients from Table A-2
- Negligible heat transfer through solid agent
- Liquid agent leaves container as the solid melts and the remaining solid settles to bottom of container.

Initially, about 79% of agent surface is in contact with metal shell. Heat transfer rate from outside air to agent surface = 2 Btu/(hr)(°F)(ft^2).

For 21% of agent surface in contact with air inside container, heat transfer rate = 0.4 Btu/(hr)(°F)(ft^2)

Thus, initially overall average heat transfer rate = 2 * 0.79 + 0.4 * 0.21 = 1.66 Btu/(hr)(°F)(ft^2)

Initially, surface area for heat transfer = 48.2 ft^2

Amount of agent around the surface to a depth of 0.025 inch

$$= \frac{0.025}{12} \text{ ft} * 48.2 \text{ ft}^2 * 80 \text{ lb/ft}^3 = 8.0 \text{ lbs}$$

Time, T_m, required to melt the first 8 lbs,

$$T_m = \frac{8 \text{ lb} * 0.273 \text{ Btu/(lb)(°F)} * 58\text{°F} * \ln\left(\frac{86-0}{86-58}\right)}{1.66 \text{ Btu/(hr)(°F)(ft}^2) * 48.2 \text{ ft}^2 * (58-0)\text{°F}}$$

$$+ \frac{8 \text{ lb} * 43.9 \text{ Btu/lb}}{1.66 \text{ Btu/(hr)(°F)(ft}^2) * 48.2 \text{ ft}^2 * (86-58)\text{°F}} = 0.187 \text{ hours}$$

Assuming 8 lbs has melted and left the container, the time is now calculated for the next layer of HD to melt. As each layer melts, the area for heat transfer, the weight of agent, and the heat transfer coefficient decreases.

Thus, after 12% of the HD has melted:

Heat transfer area = 44.5 ft^2
Amount of agent in 0.025-inch layer = 7.4 lbs
Average heat transfer coefficient = 1.2 Btu/(hr)(°F)(ft^2)
Time required to melt 7.4 lbs, T_m = 0.26 hours

The total time required to melt the HD is the sum of the times required to melt each layer. 12% of the HD will melt in 6 hours.

B.4 ESTIMATE RATE OF LIQUID TEMPERATURE RISE AFTER ACCIDENT

Scenario: An accident occurs in which the agent containment fails. Liquid agent (GB or VX) flows out of break in casing, if solid (HD), liquid flows out as agent melts.

Sample calculation for GB bulk container

Basis:

- Ambient temperature = 86°F
- Initial agent temperature = 0°F
- Heat transfer coefficient 2 Btu/(hr)(°F)(ft^2)

(Combines heat transfer rate from ground and from air, assuming wind velocity of 1 m/sec.

- 20 lb of GB evaporates during first hour (see Appendix B-6)
- Agent forms a pool 0.25 inch deep (per D2PC)

Let t_1, = temperature after 1 hour

$$\frac{2\ \text{Btu/(hr)(°F)(ft}^2) * (t_1-0)\text{°F} * 1500\ \text{lb} * 1\ \text{hour}}{\ln\left(\frac{86-0}{86-t_1}\right) * 68.8\ \text{lb/ft}^3 * \left(\frac{0.25}{12}\right)\text{ft}}$$

$$= 1500\ \text{lb} * 0.37\ \text{Btu/(lb)(°F)} * (t_1,-0)\text{°F} + 20\ \text{lb} * 141\ \text{Btu/lb}$$

Solving for t_1,

t_1 = 83.6°F

B.5 ESTIMATE EVAPORATION RATE

Evaporation rates are assumed to be proportional to vapor pressure. Time weighted average vapor pressure is used to adjust rates calculated using D2PC plume dispersion model.

Sample calculation for GB bulk container spill which is contained in 1 hour; P = vapor pressure (mm Hg) at temperature t; t = temperature (°F) of GB spill at time = T.

$$\ln (86-t) = \int_{T=0}^{T=1} (\ln 86 - 3.771T)\, dT \text{ (see computation 5, above)}$$

$$\log_{10} P = \frac{2478}{\frac{t-32}{1.8} + 273} + 8.725 \text{ (from Table A-1)}$$

Solving for P, time-weighted average vapor pressure = 2.305 mm Hg

GB evaporated during 1 hour

$$= \text{1-hour evaporation @ 86°F} * \frac{\text{average vapor pressure}}{\text{vapor pressure at 86°F}}$$

$$\text{GB evaporates from 1500 lb spill} = 32 \text{ lbs} \times \frac{2.305}{3.67} = 20 \text{ lbs}$$

One-hour evaporation @86°F calculated by D2PC model at the following conditions:

Temperature	86°F
Pasquill Stability	E
Wind Velocity	1 m/sec

APPENDIX C

CHILLING CHEMICAL MUNITIONS BY REFRIGERATION IN STORAGE MAGAZINES

CHILLING CHEMICAL MUNITIONS BY REFRIGERATION IN STORAGE MAGAZINES

At six out of eight sites where the chemical munitions stockpile is located most of the munitions are stored in magazines, or "igloos". These are concrete buildings shaped like Quonset huts with an earth cover not less than two feet thick. The typical internal dimensions are: 12'-9" high at the crown of the semi-circular arch and from 60 to 89 feet long.

An igloo can be refrigerated by circulating air from the igloo through a refrigeration unit located outside the igloo. There are a number of ways this could be done, ranging from installing a small refrigeration unit at each igloo to using a small number of larger units which could be moved from one igloo to another.

A small refrigeration unit with a rated capacity of about five tons could chill an igloo full of munitions in about 40 days (see sample calculation in Appendix B-1). A larger unit could chill the munitions faster if a method of forced air circulation could be provided inside the igloo. However, a significantly larger refrigeration unit does not appear to be feasible because it would require cutting a large opening in the igloo wall (to allow for a sufficiently high air circulation rate). We believe this could not be done safely without moving the munitions out of the igloo.* Therefore, the proposed igloo refrigeration system utilizes a unit with a five-ton capacity.

A five-ton refrigeration unit could be installed on every igloo. Chilling could be started about six weeks prior to the start of the shipping schedule to assure meeting the requirements of the schedule.

Alternatively, movable refrigeration units (mounted on skids) could be installed on a smaller number of igloos. After the munitions are chilled and moved, the refrigeration units could be moved to other igloos. The number of units that would be required depends on the shipping schedule. Since the tightest schedule is for the movement of rockets, the number of refrigeration units is determined by the schedule for rocket movements. For example, if trains are used to move rockets on a cycle which allows a train to be loaded every week (every four weeks at each of the four sites storing rockets), the schedule can be met by installing 12 movable igloo refrigeration units at each site. On this

---

*The Army regulation pertaining to repair of storage magazines where explosives are stored states: "Under no circumstances shall repairs be made to the interior of magazines containing bulk explosives." (AMC-R, 385-100, 18 - 12). It would appear that the intent of this regulation is to prohibit the igloo modifications required.

schedule, the rockets could be moved in 54 weeks. This is based on the following conditions:

- Allow eight weeks for chilling the rockets plus one week to move rockets out of an igloo and three weeks to dismantle and move a unit to the next igloo.
- Each train load is the equivalent of up to four igloos full of rockets.
- Fourteen train loads are required to move the rocket inventory from Pine Bluff, which has the largest number in storage.
- The refrigeration cycle is started at least eight weeks prior to the start of munition movement.
- Rockets are moved before the other munitions are moved.

Five hundred sixty containers are needed to maintain shipments to the schedule described above. A more relaxed schedule of one train load every two weeks would allow the movement to be performed with 280 containers and would reduce the required number of igloo refrigeration units to eight per site. At Pueblo, where no rockets are stored, eight refrigeration units are adequate to meet either movement schedule.

Five-ton Skid-mounted Refrigeration Unit

A five-ton unit should deliver an average of about 4.3 tons of refrigeration (51,600 Btu/hr), considering the non-standard operating conditions. An air circulation rate of 5,000 cfm is required. The generator supplying power should be located as far as practicable from the front of the igloo where munition handling operations are performed. This precaution is necessary to prevent munition exposure to a fire in the remote event of a fire involving the generator fuel.

Each igloo has a vent at the rear and air intakes near the door. We suggest installing an insulated duct on the vent and modifying the air intakes so that a 36" duct can be installed there, as shown in Figure C-1. All ducts should be constructed of reinforced plastic to prevent electrical charges from lightning from being carried into the igloo. Ducts must be heavily insulated. Since cooling the air will reduce its volume, replacement air will enter the system through an air intake valve. To prevent agent vapor leakage to the outside, the igloo should be maintained at a small negative pressure, which can be controlled by exhausting a small amount of air with an exhaust fan. We also suggest that this air be monitored for agent.

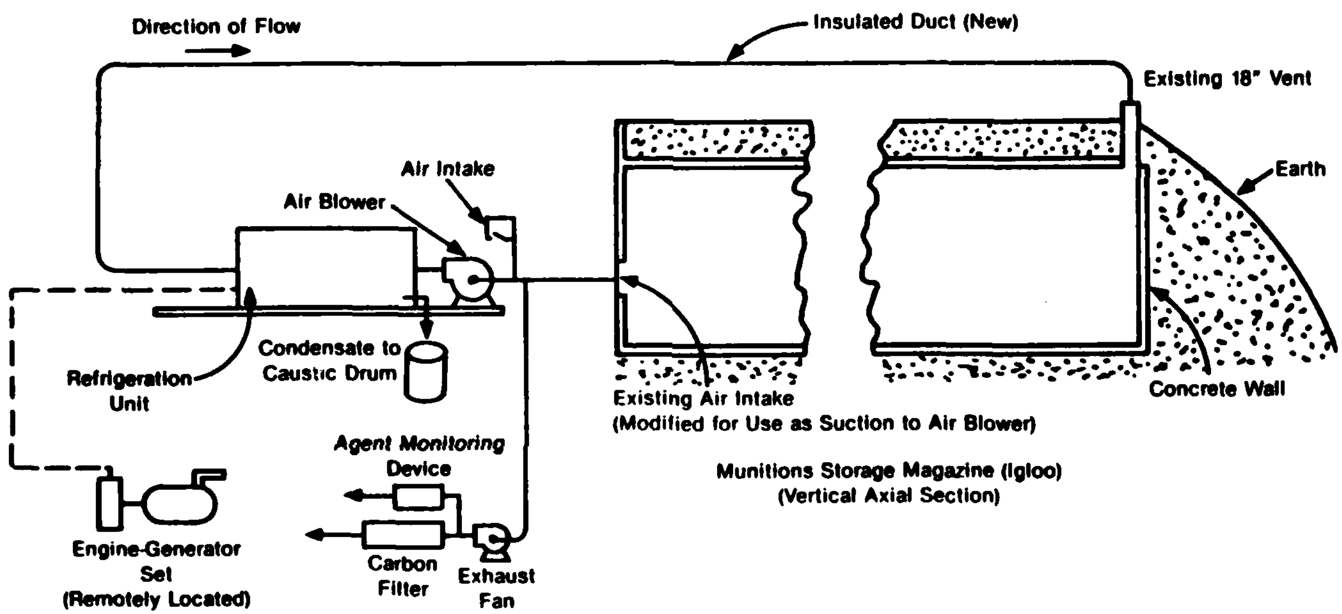

FIGURE C-1
SKETCH OF IGLOO REFRIGERATION SYSTEM

The igloo should be sealed during cooling to prevent warm air from entering. The door and, if possible, the front wall should be insulated. We believe it would be impractical to insulate other surfaces of the igloo because of the difficulty of performing such a task without removing munitions from the igloo.

One way to determine whether the agent has reached the desired temperature would be to place several tubes containing a substance with the same heat capacity as the agent in various locations about the igloo. When the temperature of the simulant reaches 0°F, it may be inferred that the agent in the munitions has reached 0°F.

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